

The distance to the Galactic Centre based on Population II Cepheids and RR Lyrae stars[★]

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ABSTRACT

Context. The distance to the Galactic Centre (GC) is of importance for the distance scale in the Universe. The value derived by Eisenhauer et al. (2005) of 7.62 ± 0.32 kpc based on the orbit of one star around the central black hole is shorter than most other distance estimates based on a variety of different methods.

Aims. To establish an independent distance to the GC with high accuracy. To this end Population-II Cepheids are used that have been discovered in the OGLE-II and OGLE-III surveys.

Methods. Thirty-nine Population-II Cepheids have been monitored with the SOFI infrared camera on 4 nights spanning 14 days, obtaining typically between 5 and 11 epochs of data. Light curves have been fitted using the known periods from the OGLE data to determine the mean K -band magnitude with an accuracy of 0.01-0.02 mag. It so happens that 37 RR Lyrae stars are in the field-of-view of the observations and mean K -band magnitudes are derived for this sample as well.

Results. After correction for reddening, the period-luminosity relation of Population-II Cepheids in the K -band is determined, and the derived slope of -2.24 ± 0.14 is consistent with the value derived by Matsunaga et al. (2006). Fixing the slope to their more accurate value results in a zero point, and implies a distance modulus to the GC of 14.51 ± 0.12 , with an additional systematic uncertainty of 0.07 mag. Similarly, from the RR Lyrae K -band period-luminosity relation we derive a value of 14.48 ± 0.17 (random) ± 0.07 (syst.). The two independent determinations are averaged to find 14.50 ± 0.10 (random) ± 0.07 (syst.), or $7.94 \pm 0.37 \pm 0.26$ kpc. The absolute magnitude scale of the adopted period-luminosity relations is tied to an LMC distance modulus of 18.50 ± 0.07 .

Key words. Stars: distances - Cepheids - RR Lyrae - Galaxy: bulge

1. Introduction

The distance to astronomical objects is a crucial parameter, yet often very difficult to obtain with high precision. The distance to the Galactic Centre (GC) is of special importance, e.g. for dynamics (Oort constants, determining distances using a rotation model), or for calibrating standard candles. The classically accepted value comes from the review by Reid (1993) and is $R_0 = 8.0 \pm 0.5$ kpc.

Over the last few years the distance to the GC based on the orbit of the star called S2 around the central black-hole (BH) has caught attention. Initially, Eisenhauer et al. (2003) derived a value of 7.94 ± 0.42 kpc which was revised by Eisenhauer et al. (2005) to 7.62 ± 0.32 kpc having more epochs of data

available. The neglect of post-Newtonian physics in these analysis may have lead to an underestimate of the distance by about 0.11 ± 0.02 kpc (Zucker et al. 2006), leading to a current best estimate of 7.73 ± 0.32 kpc (corresponding to a distance modulus (DM) of 14.44 ± 0.09) to the GC based on the BH.

On the other hand, most other recent distance determinations give a longer distance, more in line with the classical value: (1) High-amplitude delta-scuti stars give 7.9 ± 0.3 kpc (McNamara et al. 2000); (2) RR Lyrae stars suggest a value of 8.8 ± 0.3 kpc (Collinge et al. 2006), 8.3 ± 1.0 kpc (Carney et al. 1995) or 8.0 ± 0.65 kpc (Fernley et al. 1987). (3) Earlier work on the Red Clump gave a longer distance of 8.4 ± 0.4 kpc (Paczynski & Stanek 1998), although Nishiyama et al. (2006) derive 7.52 ± 0.10 (stat) ± 0.35 (syst) kpc, and Babusiaux & Gilmore (2005) 7.7 ± 0.15 kpc; (4) From a comparison of Miras found in the OGLE database in the direction of the Galactic Bulge (GB) to those in the Magellanic

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[★] Based on observations collected at the European Southern Observatory, Chile (ESO Programme 079.B-0107).

Clouds, Groenewegen & Blommaert (2005) find a distance in the range 8.5 to 9.0 kpc, in agreement with earlier work on Miras (Catchpole et al. 1999); (5) Analysis of the Hipparcos proper motions of 220 Cepheids lead to $R_0 = 8.5 \pm 0.5$ kpc (Feast & Whitelock 1997); (6) Modelling the observed colour-magnitude diagram in V , I and J , K using a population synthesis code, Vanhollebeke et al. (2008) derive a distance of 8.60 ± 0.16 kpc.

With the exception of some Red Clump based distances, the results obtained by Eisenhauer et al. imply a much shorter distance to the GC than found by most other methods, and this calls for an independent investigation of this matter.

In this paper the distance to the GC is determined using Population II Cepheids (hereafter P2C) discovered in the OGLE micro-lensing survey, and for which the mean K -band magnitude will be determined by infrared monitoring. Comparing to the calibrated P2C period-luminosity (PL) relation in the K -band from Matsunaga et al. (2006; hereafter M06) then provides the distance, after correction for reddening.

In addition, the mean K -band magnitude will be determined for RR Lyrae stars that are in the field, and compared to the calibrated K -band PL-relation from Sollima et al. (2006). The Matsunaga et al. and Sollima et al. relations both imply an LMC DM of 18.50 as detailed in Sect. 5.

In Sect. 2 the sample is discussed, and the observations are presented in Sect. 3 for the P2C and Sect. 3 for the RR Lyrae. The results are discussed in Sect. 5.

2. The sample of Population II Cepheids

Population-II Cepheids are old, low-mass stars. They are the progeny of hot HB stars that after the exhaustion of core He-burning, move toward lower effective temperatures (post-early AGB), thus crossing the Cepheid instability strip. They are systematically brighter than RR Lyrae stars and have periods ranging from slightly below one to a few tens of days

Kubiak & Udalski (2003; hereafter KU) have searched the OGLE-II database for P2C Cepheids and found 54 objects. KU determined a period-luminosity relation in the reddening-free Wesenheit index (based on V , I photometry) and compared it to P2C Cepheids in the LMC. The difference in DM at a typical period of $\log P = 0.5$ is 3.58. By assuming a DM for the LMC of 18.5 (50.1 kpc) the distance to the GC P2C becomes 9.6 kpc (with a substantial error bar of 1.5 kpc). This places the objects nominally in the GB region. Additional evidence is that KU found these objects to be located in a bar (see their Fig. 2), like the RR Lyrae (Collinge et al. 2006), a strong indication that the P2C Cepheids indeed are physically part of the GC region. These properties gave us the confidence that determining individual distances to these objects would indeed provide an accurate distance determination to the GC.

A subset of stars was selected based on the following criteria: The I -band light curves of these stars were inspected and only “smooth” ones were retained that show no or little effect of shocks in the atmosphere (Figure 1 shows two examples). The range in Galactic longitude was largely restricted to $-2.5 \lesssim l \lesssim +2.5$ degrees to avoid any additional smearing in distance

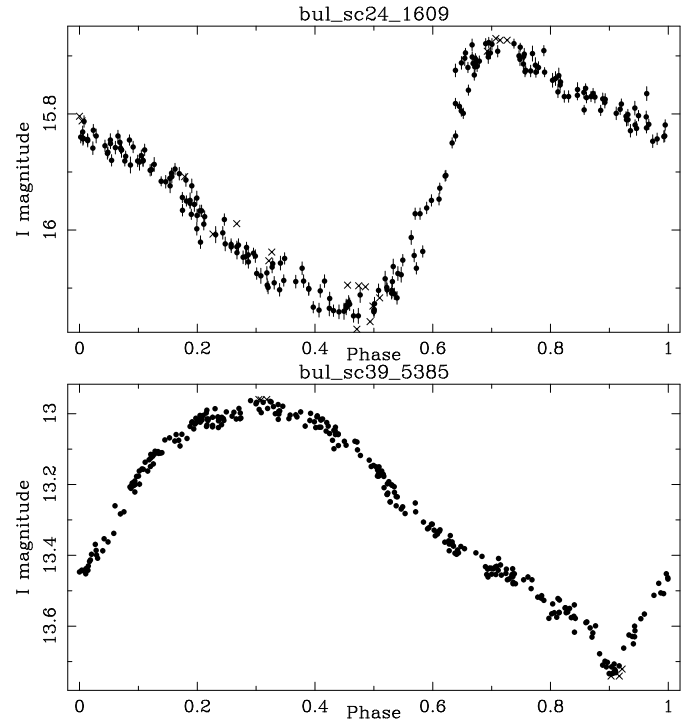


Fig. 1. Phased OGLE I -band light curves of two of the P2C. The periods of the two stars are 0.76522 (bul_sc24_1609) and 9.94431 (bul_sc39_5385) days.

due to the effect of the inclination of the bar. The entire period range from 0.8 to ± 10 days should be covered. OGLE I -band images were inspected for crowding.

In a later stage, it was also possible to extend the sample with the first results from the ongoing OGLE-III survey and a sample of 70 new P2C in the longitude range -2.5 to $+2.5$ degrees could be added. After inspecting the light curves and I -band images of these stars as well, a final combined sample of 49 stars remained, of which 39 were actually monitored.

The basic properties of the sample are listed in Table 1 in the first columns: Identification, R.A., Declination, pulsation period, galactic coordinates.

3. The observations

The observations were carried out with the SOFI infra-red camera on the 3.5m NTT on ESO/La Silla in the nights of 2007, June 24, 28, July 3, 8 in visitor mode.

Photometric conditions were excellent on the second and third night with seeing as low as $0.6''$ and the telescope was actually defocused. Weather conditions were poorer on the first and last night with seeing in the range 1.5 – $2''$ and cirrus and thin clouds. As the measurements of the P2C will be relative to the 2MASS objects in the field this additional extinction did not influence this program.

Typically it was tried to observe the longest period ($\gtrsim 7$ d) Cepheids at the beginning and end of the night, the intermediate period ones ($\gtrsim 3$ d) three times per night, and the shorter period ones were observed one after the other over the entire night. In total we obtained 362 epochs of data of 39 P2C.

Images in the K_s band (hereafter simply K -band) were taken with the shortest possible on-chip integration time of $\text{DIT} = 1.2$ seconds using a pixel-scale of $0.288''$ and resulting in a field-of-view of almost $5 \times 5 \text{ arcmin}^1$. The “auto-jitter” observing block (OB) was used with 9-13 exposures. The relative large number was used to have sufficient redundancy in creating a sky image in these relatively crowded fields. The K -band was chosen for the observations as the dispersion in the PL -relation is smaller in that band than in J or H (M06).

The data were reduced with the newly released SOFI data reduction pipeline². The pipeline takes into account the cross-talk, the flat-field (dome flats taken with a special OB), bad pixel cleaning, and images correlation and reconstruction.

The reduced images were trimmed to the original 1024×1024 pixel size to eliminate the under exposed edges. The astrometric solution was done using the WCSTools suite³ matching the stars in the field against the 2MASS catalog. Typically several tens of 2MASS objects are available and the rms in the solution typically is $0.2''$. Source extraction and PSF photometry was done using version 1.3 of DoPhot (Schechter et al. 1993). A dedicated Fortran program was written to match the 2MASS objects with the sources in the field, and determine the offset between the instrumental magnitude and the 2MASS K_s -band magnitude. The brightest and faintest 2MASS objects were excluded to avoid problems of saturation in the SOFI images and poor quality 2MASS data. A straight line was fitted to the data, and this determined the offset to be applied to the SOFI instrumental magnitudes to put them on the 2MASS system (an example is shown in Fig. 2). The typical error in the determination of this offset is 0.006 mag , and this is added in quadrature to the error in the instrumental magnitude for each star to give the total error in the observed magnitude.

This error is verified by comparing the magnitudes over the different epochs for field stars and estimating the precision with which the mean magnitude can be determined.

After having determined the photometric offsets, the light curves of the P2C could be constructed. The light curves were then fitted with a sine-function with the known period from the OGLE data, and this allowed the determination of the mean K -magnitude with high precision. Figure 3 shows the (phased) light curve for two P2C Cepheids with a short and long period in the sample. The last three columns of Tab. 1 list the mean K -band magnitude, the precision in this determination and the number of epochs.

4. RR Lyrae stars

Collinge et al. (2006) present a catalog of 1888 fundamental-mode RR Lyrae stars in the OGLE fields. It was verified which of them happen to be located in the SOFI fields of view, and for those the K -band light curve was extracted, and fitted with a sine-curve with the known period. Table 2 present the results, with columns 2-4 taken from Collinge et al. Column 5 lists in which P2C field it is located and in the analysis the corre-

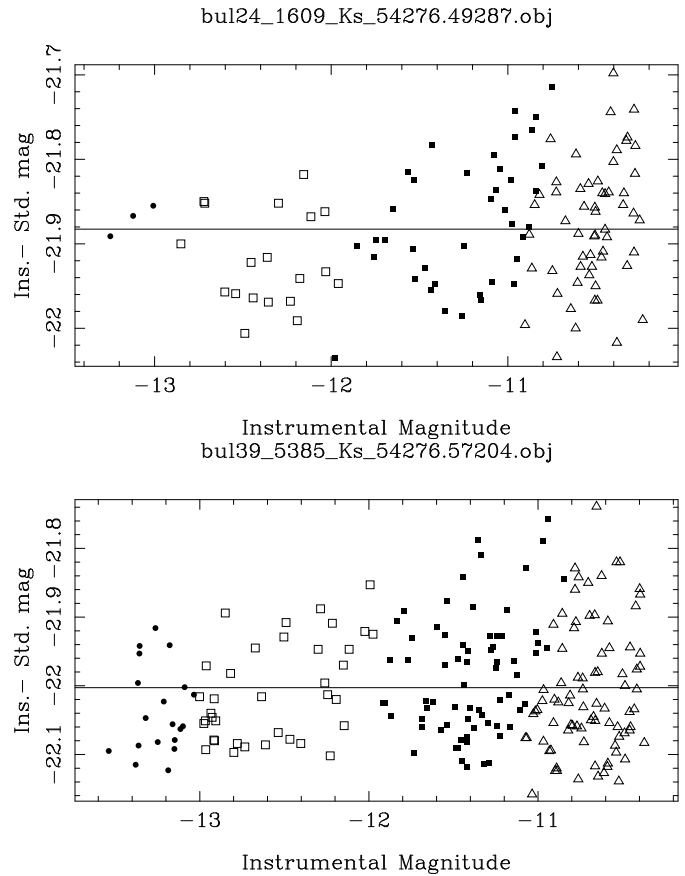


Fig. 2. The difference between SOFI instrumental magnitude and 2MASS magnitude versus instrumental magnitude for a single epoch for two different objects. The symbols indicate different 1 magnitude bins in 2MASS magnitude.

sponding reddening for that field is taken (see below). The last columns lists the mean magnitude, the error, and the number of epochs. Figure 4 shows the light curve for 2 stars.

5. Analysis

5.1. P2C: K -band PL -relation

The K -band magnitudes are de-reddened using the model by Marshall et al. (2006). They present 3-dimensional K_s -band extinction along 64 000 lines of sight at a resolution of $15'$ in typically four distance bins. Using VizieR⁴ the available data within $20'$ radius of the targets were retrieved. The mean and dispersion was determined of the A_K values in the bin that correspond to a distance larger than 4 kpc (for 2 stars a smaller distance had to be adopted). Table 1 lists in Columns 7-9 the mean, dispersion and the number of data points used.

Columns 10 of this table list the A_K value derived by multiplying by 0.12 (based on the reddening law of Cardelli et al. 1989) the A_V value for the OGLE-II GB fields by Sumi (2004).

Based on the MACHO survey towards the GB Popowski et al. (2003) derive visual extinction for 9717 elements at a resolution of about $4'$. The available data within $5'$ radius of the tar-

¹ The $0.144''$ pixel scale was unfortunately no longer offered.

² Available at <http://www.eso.org/sci/data-processing/software/pipelines/>

³ available at <http://tdc-www.harvard.edu/software/wcstools/>

⁴ <http://vizier.u-strasbg.fr/viz-bin/VizieR>

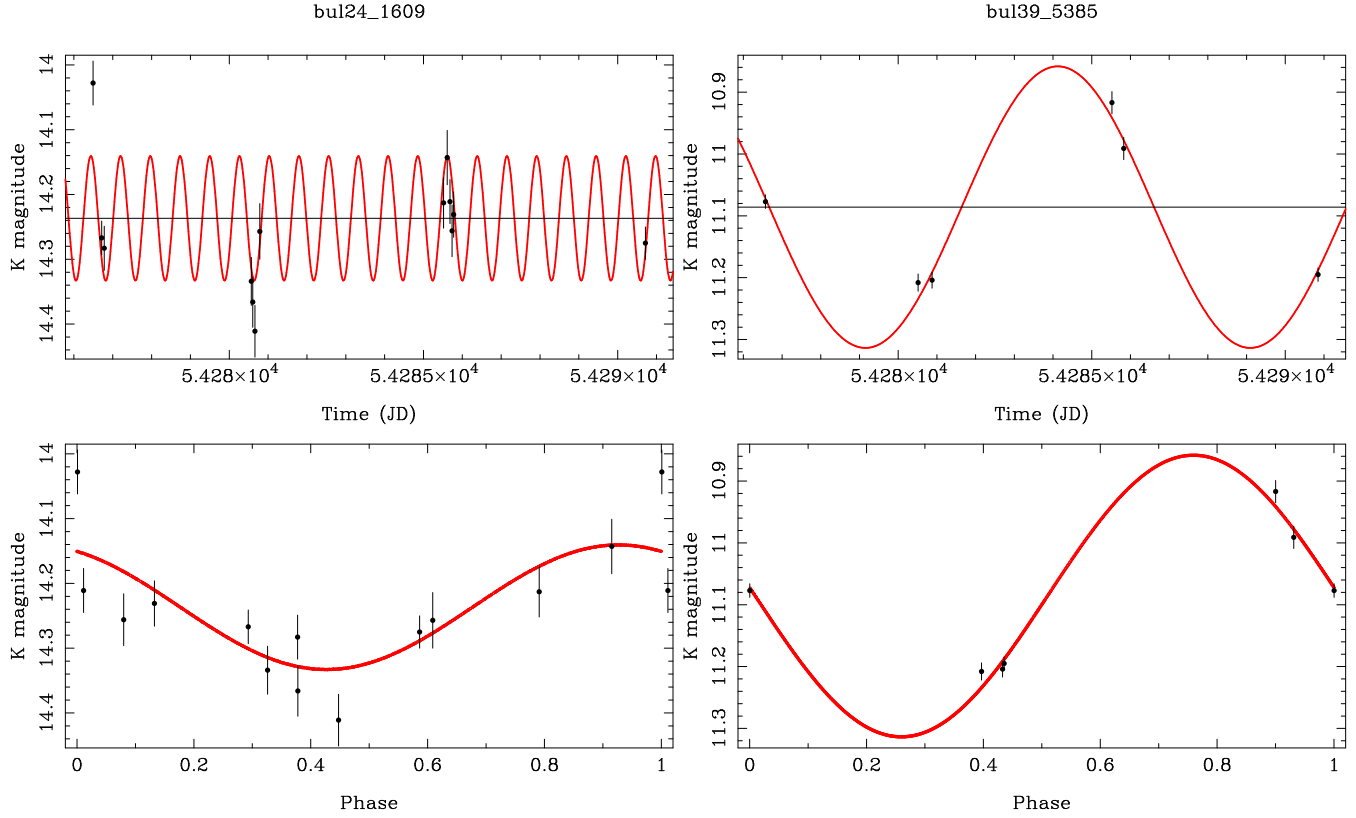


Fig. 3. The *K*-band light curves of two P2C. The top panel shows the magnitude versus time, the bottom panel the phased light curve.

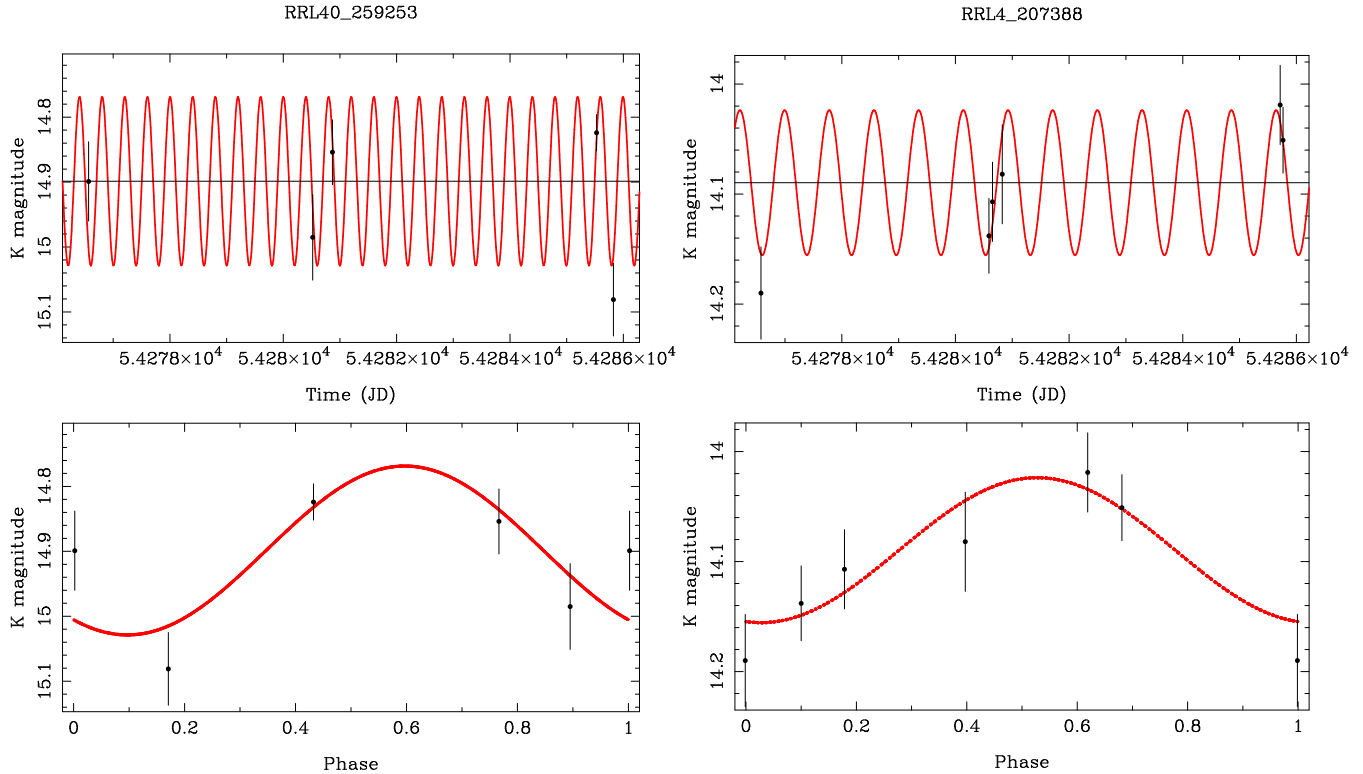


Fig. 4. The *K*-band light curves of two RR Lyrae. The top panel shows the magnitude versus time, the bottom panel the phased light curve.

Table 1. The sample of Cepheids, ordered by period.

| Name | RA (J2000) | DEC (J2000) | Period (days) | l | b | $A_K^{(1)}$ | σ | n | $A_K^{(2)}$ | $A_K^{(3)}$ | σ | n | K | σ | n |
|-----------------|---------------|----------------|------------------|--------|-------|-------------|----------|-----|-------------|-------------|----------|-----|--------|----------|-----|
| bul24_1609 | 17 53 44.41 | -32 57 14.0 | 0.76522 | 357.44 | -3.56 | 0.284 | 0.018 | 6 | 0.302 | - | - | - | 14.237 | 0.010 | 13 |
| bul214.2_135 | 17 57 35.12 | -28 26 11.6 | 0.82684 | 1.77 | -2.00 | 0.317 | 0.028 | 5 | - | 0.354 | 0.011 | 6 | 13.805 | 0.049 | 5 |
| bul214.6_53717 | 17 56 15.76 | -28 14 02.3 | 0.83088 | 1.80 | -1.65 | 0.352 | 0.005 | 3 | - | - | - | - | 14.118 | 0.057 | 6 |
| bul39_2239 | 17 56 05.04 | -29 54 51.8 | 0.92213 | 0.33 | -2.46 | 0.275 | 0.026 | 6 | 0.316 | 0.343 | 0.023 | 6 | 13.836 | 0.023 | 6 |
| bul22_3993 | 17 56 33.03 | -30 36 33.5 | 0.93110 | 359.77 | -2.89 | 0.330 | 0.051 | 6 | 0.329 | - | - | - | 13.583 | 0.013 | 9 |
| bul31_662 | 18 01 56.92 | -28 55 11.6 | 0.93951 | 1.82 | -3.07 | 0.193 | 0.019 | 6 | 0.217 | 0.237 | 0.021 | 3 | 13.925 | 0.010 | 8 |
| bul43_351 | 17 35 08.13 | -27 31 25.8 | 1.09776 | 359.97 | 2.71 | 0.492 | 0.045 | 6 | 0.440 | - | - | - | 13.629 | 0.007 | 13 |
| bul163.7_46320 | 17 51 54.32 | -31 56 39.8 | 1.21123 | 358.12 | -2.71 | 0.433 | 0.078 | 4 | - | - | - | - | 12.573 | 0.010 | 11 |
| bul30_1107 | 18 01 47.33 | -29 07 39.1 | 1.33916 | 1.63 | -3.14 | 0.215 | 0.016 | 4 | 0.229 | 0.233 | 0.015 | 4 | 12.126 | 0.006 | 11 |
| bul215.7_107864 | 17 58 54.55 | -28 21 30.8 | 1.40015 | 1.98 | -2.22 | 0.282 | 0.035 | 6 | - | 0.278 | 0.011 | 4 | 13.088 | 0.009 | 11 |
| bul3_791 | 17 53 27.82 | -30 19 55.3 | 1.48412 | 359.68 | -2.18 | 0.323 | 0.049 | 5 | 0.347 | - | - | - | 14.255 | 0.022 | 8 |
| bul5_3719 | 17 50 21.49 | -29 54 27.5 | 1.50105 | 359.70 | -1.39 | 0.310 | 0.023 | 4 | 0.688 | - | - | - | 13.304 | 0.028 | 7 |
| bul32_2167 | 18 02 56.05 | -28 40 39.2 | 1.50523 | 2.14 | -3.14 | 0.178 | 0.012 | 4 | 0.193 | 0.212 | 0.011 | 5 | 13.351 | 0.008 | 11 |
| bul4_170 | 17 54 38.21 | -30 10 41.8 | 1.53185 | 359.94 | -2.32 | 0.278 | 0.027 | 5 | 0.311 | - | - | - | 13.027 | 0.010 | 10 |
| bul44_5324 | 17 49 30.95 | -29 50 58.2 | 1.55140 | 359.66 | -1.20 | 0.313 | 0.039 | 5 | 0.720 | - | - | - | 13.449 | 0.011 | 8 |
| bul188.1_11087 | 17 59 30.71 | -30 19 59.7 | 1.69825 | 0.33 | -3.31 | 0.271 | 0.045 | 5 | - | - | - | - | 12.904 | 0.018 | 9 |
| bul21_3035 | 17 59 53.52 | -28 56 37.5 | 1.73020 | 1.58 | -2.69 | 0.198 | 0.019 | 5 | - | 0.219 | 0.014 | 5 | 13.159 | 0.017 | 9 |
| bul45_1189 | 18 03 33.61 | -30 01 14.6 | 1.74795 | 1.04 | -3.92 | 0.177 | 0.019 | 6 | 0.220 | 0.169 | 0.009 | 5 | 13.125 | 0.018 | 9 |
| bul23_611 | 17 58 14.58 | -31 33 23.7 | 1.85470 | 359.13 | -3.68 | 0.312 | 0.009 | 4 | 0.324 | - | - | - | 12.783 | 0.007 | 10 |
| bul34_4631 | 17 58 01.53 | -28 59 56.6 | 2.33010 | 1.33 | -2.37 | 0.234 | 0.031 | 4 | 0.302 | 0.312 | 0.033 | 5 | 12.690 | 0.024 | 9 |
| bul20_961 | 17 58 55.93 | -29 10 57.0 | 2.88445 | 1.27 | -2.63 | 0.223 | 0.038 | 6 | 0.233 | 0.219 | 0.004 | 5 | 12.661 | 0.006 | 9 |
| bul41_3841 | 17 51 42.51 | -32 41 41.3 | 3.20082 | 357.45 | -3.06 | 0.346 | 0.028 | 5 | 0.318 | - | - | - | 12.196 | 0.008 | 9 |
| bul4_8846 | 17 54 06.61 | -29 16 22.1 | 3.51336 | 0.66 | -1.76 | 0.295 | 0.025 | 5 | 0.311 | - | - | - | 12.449 | 0.012 | 6 |
| bul4_2323 | 17 54 55.52 | -29 57 31.0 | 3.54254 | 0.16 | -2.26 | 0.271 | 0.022 | 6 | 0.311 | 0.286 | 0.010 | 5 | 13.267 | 0.112 | 4 |
| bul39_616 | 17 55 12.35 | -30 07 24.1 | 3.65017 | 0.05 | -2.40 | 0.268 | 0.023 | 4 | 0.316 | - | - | - | 12.281 | 0.007 | 8 |
| bul195.4_144166 | 17 53 40.70 | -28 56 47.0 | 3.82791 | 0.90 | -1.52 | 0.315 | 0.024 | 4 | - | - | - | - | 12.101 | 0.014 | 4 |
| bul22_815 | 17 56 46.47 | -31 07 07.3 | 4.49944 | 359.36 | -3.19 | 0.270 | 0.031 | 5 | 0.329 | - | - | - | 12.415 | 0.035 | 7 |
| bul3_1755 | 17 53 34.75 | -30 12 39.7 | 4.57875 | 359.80 | -2.14 | 0.318 | 0.046 | 6 | 0.347 | - | - | - | 12.613 | 0.055 | 7 |
| bul38_3260 | 18 01 32.68 | -29 49 11.5 | 5.53097 | 1.00 | -3.44 | 0.214 | 0.027 | 7 | 0.220 | 0.206 | 0.018 | 4 | 12.175 | 0.121 | 5 |
| bul180.5_151030 | 17 51 57.55 | -30 21 39.2 | 6.89131 | 359.49 | -1.91 | 0.381 | 0.042 | 5 | - | - | - | - | 11.601 | 0.007 | 6 |
| bul20_3867 | 17 58 55.95 | -28 43 19.5 | 7.13700 | 1.67 | -2.40 | 0.233 | 0.031 | 4 | 0.233 | 0.243 | 0.012 | 5 | 11.639 | 0.007 | 6 |
| bul2_1657 | 18 04 19.87 | -29 02 44.2 | 7.45600 | 1.97 | -3.59 | 0.174 | 0.007 | 6 | 0.186 | 0.189 | 0.014 | 4 | 11.464 | 0.007 | 6 |
| bul25_693 | 17 54 24.38 | -33 06 51.0 | 7.73934 | 357.37 | -3.76 | 0.275 | 0.020 | 6 | 0.281 | - | - | - | 11.775 | 0.006 | 6 |
| bul40_2524 | 17 50 58.92 | -33 08 53.1 | 7.77000 | 356.98 | -3.16 | 0.344 | 0.022 | 6 | 0.353 | - | - | - | 11.999 | 0.006 | 6 |
| bul214.5_169880 | 17 56 37.75 | -28 01 28.4 | 8.07957 | 2.02 | -1.61 | 0.367 | 0.050 | 5 | - | 0.462 | 0.017 | 5 | 12.180 | 0.007 | 5 |
| bul7_540 | 18 08 44.36 | -32 13 10.6 | 9.52109 | 359.64 | -5.95 | 0.149 | 0.004 | 4 | 0.160 | - | - | - | 11.220 | 0.006 | 6 |
| bul39_5385 | 17 55 23.12 | -29 31 35.3 | 9.94431 | 0.58 | -2.13 | 0.278 | 0.025 | 4 | 0.316 | 0.323 | 0.006 | 4 | 11.086 | 0.007 | 6 |
| bul334.7_59737 | 17 40 50.79 | -25 03 52.7 | 11.38492 | 2.74 | 2.94 | 0.456 | 0.036 | 7 | - | - | - | - | 14.200 | 0.018 | 5 |
| bul333.2_25311 | 17 36 34.05 | -27 18 08.3 | 14.89102 | 0.33 | 2.56 | 0.449 | 0.034 | 4 | - | - | - | - | 10.856 | 0.008 | 5 |

Notes:

(1) Reddening from Marshall et al. (2006). (2) Reddening based on Sumi (2004). (3) Reddening based on Popowski et al. (2003).

gets was retrieved. The mean and dispersion was determined, and multiplied by 0.12 to obtain the K -band extinction, which is listed with the number of elements used as Columns 11-13 in Table 1.

The comparison of the reddenings based on the Marshall et al. model and the values from Sumi and Popowski et al. suggest that there are no systematic effects and that the error in the adopted reddening is realistic.

The observed K -magnitudes are then de-reddened, and Fig. 5 shows for the P2C the observed period-luminosity relation in the K -band, together with the best-fitting line (excluding the cross), $K_0 = (-2.24 \pm 0.14)(\log P - 1.2) + (10.578 \pm 0.099)$, with an rms of 0.41 mag. This is based on a weighted least-squares fit, where the error in A_K is added in quadrature

to the error in K . Eliminating the possible three outliers near a period of 1.3 days gives a slope of -2.41 ± 0.08 and a ZP of 10.529 ± 0.059 with an rms of 0.28 mag.

This dispersion is largely due to the intrinsic depth of the Bulge which is of the order of 1 kpc (e.g. Babusiaux & Gilmore 2005), and was already seen in the dispersion around the Wesenheit PL -relation by KU.

Plotting the residuals versus galactic longitude and latitude suggested a slight dependence on these parameters, and a general linear fit was made (excluding only one object):

$$K_0 = (-2.24 \pm 0.13)(\log P - 1.2) + (10.60 \pm 0.17)$$

$$+ (-0.028 \pm 0.031) l + (0.005 \pm 0.031) b \quad (1)$$

Table 2. The sample of RR Lyrae stars, ordered by period.

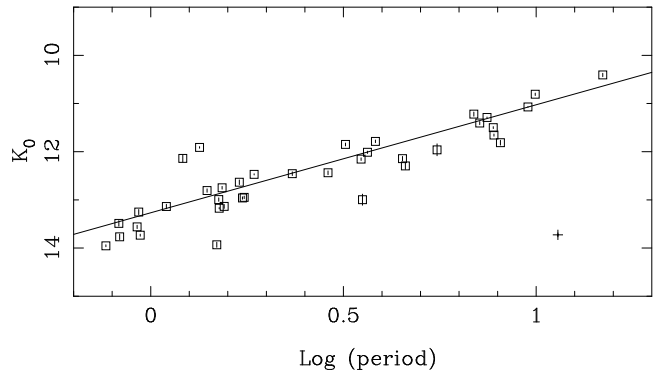
| Name | RA (J2000) | DEC (J2000) | Period (days) | P2C field | K | σ | n | remark |
|--------------|---------------|----------------|------------------|------------|--------|----------|-----|---------|
| bul40_259253 | 17.85087 | -33.1519 | 0.39951 | bul40_2524 | 14.899 | 0.021 | 5 | |
| bul39_15393 | 17.92076 | -30.1590 | 0.43787 | bul39_616 | 12.685 | 0.017 | 6 | outlier |
| bul31_680405 | 18.04767 | -28.6609 | 0.43940 | bul32_2167 | 14.536 | 0.011 | 11 | |
| bul45_245148 | 18.05646 | -30.0464 | 0.44022 | bul45_1189 | 14.410 | 0.010 | 8 | |
| bul20_43721 | 17.98309 | -29.1750 | 0.45910 | bul20_961 | 14.399 | 0.013 | 8 | |
| bul24_369931 | 17.89280 | -32.9691 | 0.47306 | bul24_1609 | 13.951 | 0.008 | 12 | |
| bul45_256663 | 18.05978 | -30.0235 | 0.47416 | bul45_1189 | 14.421 | 0.018 | 7 | |
| bul3_239578 | 17.89180 | -30.3038 | 0.48308 | bul3_791 | 14.605 | 0.082 | 4 | |
| bul22_133009 | 17.93951 | -30.6361 | 0.48700 | bul22_3993 | 14.331 | 0.011 | 9 | |
| bul44_201914 | 17.82289 | -29.8616 | 0.48806 | bul44_5324 | 11.237 | 0.006 | 6 | outlier |
| bul20_44361 | 17.98202 | -29.1714 | 0.48950 | bul20_961 | 14.994 | 0.021 | 6 | |
| bul4_207615 | 17.90976 | -30.1619 | 0.50215 | bul4_170 | 14.405 | 0.028 | 7 | |
| bul31_23420 | 18.03285 | -28.9437 | 0.50610 | bul31_662 | 12.923 | 0.020 | 5 | outlier |
| bul22_219909 | 17.94488 | -31.1046 | 0.52411 | bul22_815 | 12.718 | 0.007 | 6 | outlier |
| bul39_156007 | 17.92021 | -29.5568 | 0.52499 | bul39_5385 | 14.119 | 0.026 | 4 | |
| bul34_159387 | 17.96703 | -28.9742 | 0.54158 | bul34_4631 | 14.437 | 0.017 | 7 | |
| bul40_107313 | 17.84697 | -33.1318 | 0.54215 | bul40_2524 | 14.430 | 0.024 | 5 | |
| bul4_451052 | 17.91352 | -29.9600 | 0.54390 | bul4_2323 | 14.185 | 0.013 | 8 | |
| bul5_261524 | 17.84023 | -29.8885 | 0.55190 | bul5_3719 | 14.320 | 0.027 | 8 | |
| bul22_402472 | 17.94676 | -31.0980 | 0.55482 | bul22_815 | 14.408 | 0.014 | 6 | |
| bul4_439650 | 17.91289 | -29.9957 | 0.55603 | bul4_2323 | 14.419 | 0.011 | 7 | |
| bul32_87588 | 18.05029 | -28.6886 | 0.57740 | bul32_2167 | 13.994 | 0.014 | 9 | |
| bul22_144794 | 17.94068 | -30.6044 | 0.57910 | bul22_3993 | 14.364 | 0.016 | 9 | |
| bul25_187102 | 17.90468 | -33.1508 | 0.57918 | bul25_693 | 14.244 | 0.015 | 5 | |
| bul22_144296 | 17.94163 | -30.5937 | 0.58562 | bul22_3993 | 14.261 | 0.012 | 9 | |
| bul43_130470 | 17.58358 | -27.5280 | 0.59590 | bul43_351 | 14.246 | 0.013 | 10 | |
| bul22_333396 | 17.94312 | -30.5768 | 0.61422 | bul22_3993 | 14.525 | 0.036 | 4 | |
| bul24_527005 | 17.89388 | -32.9262 | 0.61678 | bul24_1609 | 14.356 | 0.011 | 10 | |
| bul3_250926 | 17.89106 | -30.2063 | 0.63179 | bul3_1755 | 13.017 | 0.013 | 6 | outlier |
| bul34_159754 | 17.96594 | -29.0003 | 0.63539 | bul34_4631 | 14.066 | 0.016 | 9 | |
| bul45_245339 | 18.05951 | -30.0290 | 0.63597 | bul45_1189 | 14.034 | 0.045 | 6 | |
| bul34_145186 | 17.96658 | -29.0164 | 0.66322 | bul34_4631 | 14.193 | 0.025 | 4 | |
| bul30_604974 | 18.03144 | -29.1517 | 0.67131 | bul30_1107 | 14.361 | 0.025 | 8 | |
| bul34_389919 | 17.96842 | -29.0303 | 0.67304 | bul34_4631 | 14.334 | 0.016 | 7 | |
| bul39_15358 | 17.92118 | -30.1017 | 0.69769 | bul39_616 | 14.323 | 0.040 | 5 | |
| bul24_517291 | 17.89567 | -32.9539 | 0.76522 | bul24_1609 | 14.237 | 0.010 | 13 | |
| bul4_207388 | 17.90973 | -30.1789 | 0.78642 | bul4_170 | 14.090 | 0.015 | 6 | |

The slope agrees within the error bar with that of the PL -relation derived by M06 which is also on the 2MASS system: $M_{K_0} = (-2.41 \pm 0.05)(\log P - 1.2) + (-4.00 \pm 0.02)$ with a dispersion of 0.14 mag.

In order to derive the distance to the GC a Monte-Carlo simulation was performed. Data sets with new values for A_K and K were generated based on the mean values and (Gaussian) errors listed in Table 1, and unweighted fits were made for a fixed slope of -2.41 . This results in a zero point (ZP) of 10.512 ± 0.013 .

The DM to the GC therefore is 14.51 ± 0.02 , corresponding to 7.99 ± 0.09 kpc. The error takes into account the precision in our ZP and the error in the ZP of the M06 relation.

Even adding in quadrature an additional 0.015 mag to the error on the photometry (allowing for an underestimate of the adapted error on the transformation from instrumental magnitude to the 2MASS system), and doubling the error on the A_K value (with a minimum error of 0.03) increases the formal error

**Fig. 5.** The K -band PL-relation for P2C in the Bulge. The line is a best-fit excluding the cross.

bar on the derived ZP only to 0.025 mag, and the error on the DM to 0.03 (0.12 kpc).

5.2. P2C: the Wesenheit-index PL-relation

An alternative method to derive the distance is to use a reddening-free Wesenheit index. The most appropriate one is $WIK = I - \alpha(I - K)$ as the I -band magnitudes are available from OGLE. Unfortunately the available I -band data (Pritzl et al. 2003) for stars with K -band data in M06 is insufficient to derive an empirical relation, but one can use theoretical PL -relations as derived in several bands by Di Criscienzo (2007). These theoretical relations are in good agreement with observations: The slope of the theoretical I -band PL -relation, -2.10 ± 0.06 , is in agreement with the observed one of -2.03 ± 0.03 (Pritzl et al. 2003), while in the K -band the theoretical slope of -2.38 ± 0.02 is in good agreement with the observed -2.41 ± 0.02 in M06. For an assumed mixing length parameter of 1.5, one needs to adopt a fiducial $[\text{Fe}/\text{H}]$ value of -1.63 in the theoretical PL -relation to obtain the observed I magnitude at a typical period of $\log P = 0.5$ (Pritzl et al. 2003), and similarly a fiducial $[\text{Fe}/\text{H}]$ of -2.55 to obtain the observed K magnitude at $\log P = 0.5$ (M06).

The theoretical relation is, depending on the coefficient α in the Wesenheit-relation (Di Criscienzo, private comm.) $WIK = (-1.13 \pm 0.02) - (2.53 \pm 0.04) \log P + (0.06 \pm 0.01)[\text{Fe}/\text{H}]$ for $\alpha_1 = 1.252$ (standard reddening law) or, $(-1.17 \pm 0.02) - (2.57 \pm 0.04) \log P + (0.06 \pm 0.01)[\text{Fe}/\text{H}]$ for $\alpha_2 = 1.316$ (allowing for anomalous reddening in I , see Sumi 2004). For an $[\text{Fe}/\text{H}]$ value of -2.0 ± 0.4 one expects ZPs of -1.25 ± 0.04 (α_1) and -1.29 ± 0.04 (α_2).

A potential complication is that the theoretical relation is derived for the Bessell & Brett (1988) photometric system, while in particular the OGLE I -filter is slightly non-standard. An appropriate transformation is applied to both the 2MASS K , and OGLE I to the Bessell & Brett system. It turns out however that for the typical $(V - I)$ colours of the P2C in the observed fields and the particular value of the slope in the Wesenheit-index the corrections largely cancel, and the effect on the derived ZP is minimal.

For α_1 the derived slope from the observations is -2.25 ± 0.17 , for α_2 -2.27 ± 0.18 . The agreement between the observed and theoretical slopes is less good (about 1.6 - 1.7σ deviation) than that in the K -band (only 1.3σ deviation).

When the slope is fixed to the theoretical value one obtains ZPs of 13.19 ± 0.01 and 13.04 ± 0.01 , respectively, based on a Monte-Carlo simulation. Depending on the reddening law adopted one obtains a DM of about 14.44 (7.73 kpc), or 14.33 (7.35 kpc) with an internal error bar of 0.04 mag (0.14 kpc).

5.3. RR Lyrae

Sollima et al. (2006) derive an empirical PLK-relation based on 15 GC and the LMC cluster Reticulum, which for a metallicity of $[\text{Fe}/\text{H}] = -1.0$ (the average metallicity of RR Lyrae in the GB, see Walker & Terndrup 1991), reads $M_K = (-2.38 \pm 0.04) \log P - (1.13 \pm 0.13)$, which was calibrated against the trigonometric parallax of RR Lyra (Benedict et al. 2002).

Removing five bright outliers the PL-relation becomes (cf. Figure 6):

$$K_0 = (-1.36 \pm 0.49) \log P + (13.63 \pm 0.17)$$

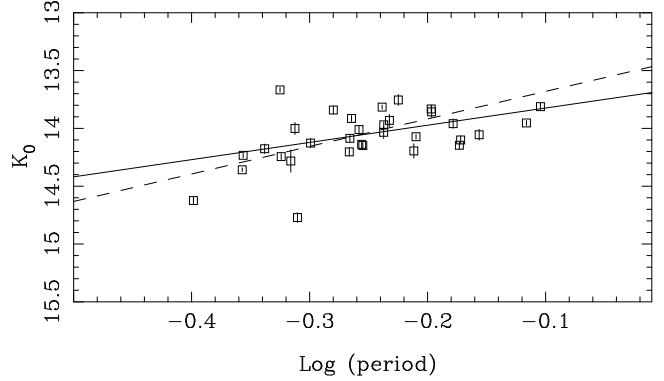


Fig. 6. The K -band PL -relation for the RR Lyrae stars in the Bulge. The line is a best-fit excluding the outliers labeled in Table 2 which fall outside the plot. The dotted line is the fit for a fixed slope of -2.38 .

$$+ (+0.019 \pm 0.021) l - (0.025 \pm 0.043) b \quad (2)$$

The error in the derived slope is large but formally agrees within 2σ with the empirical slope by Sollima et al. For a fixed slope of -2.38 , the ZP becomes 13.39 ± 0.13 (based on a Monte-Carlo simulation), resulting in a DM of 14.52 ± 0.18 (8.0 ± 0.7 kpc).

6. Discussion

The PL -relation in the K -band of P2C in the GB is derived. The slope is found to be in agreement with that derived by M06. Fixing the slope to their more accurate value implies a DM to the GC of 14.51 with a formal error bar of 0.03 .

There is also the systematic error bar to consider. M06 presented JHK period-luminosity relations based on 46 P2C with periods between 1.2 and 80 days in 26 Galactic globular clusters (GCs). For the absolute magnitude scale they adopted a relation between absolute V -magnitude of the Horizontal Branch and metallicity (Gratton et al. 2003), which in turn is calibrated using main-sequence fitting to three GCs. This calibration implies an RR Lyrae based LMC DM of 18.50 ± 0.09 (Gratton et al. 2003). M06 show that the DM based on P2C in the LMC and their K -band PL -relation is also compatible with 18.5 .

They also show that there is no significant trend with metallicity over the range $-2.2 \lesssim [\text{Fe}/\text{H}] \lesssim -0.5$, in agreement with theoretical predictions (Bono et al. 1997, 2003, Di Criscienzo et al. 2007), and indicating that this K -band PL -relation should be applicable for GC P2C as well. The metallicity of the P2C in the Bulge is unknown but that of RR Lyrae is estimated to be on average $[\text{Fe}/\text{H}] = -1.0$ (Walker & Terndrup 1991). Any difference between that metallicity and the mean metallicity of about $[\text{Fe}/\text{H}] = -1.5$ of the GCs in M06 would result in an uncertainty in the ZP of $\lesssim 0.03$ mag.

Di Criscienzo et al. (2007) show that adopting a different M_V - $[\text{Fe}/\text{H}]$ relation has a negligible effect on the derived slope of the NIR PL -relations.

The ZP in the calibrating relation by Gratton et al. has a formal error of 0.07 and this has to be considered as a source of systematic uncertainty in the derived distance.

There is other source of (random) error to consider, namely how representative this particular set of 39 stars (minus the one outlier) that defines the PL -relation is in view of the fact that they scatter along the line-of-sight due to the intrinsic depth of the Bulge. To simulate this, additional Monte-Carlo simulations were carried out. Random samples of 38 stars were selected from the original sample, and the PL -relation re-derived. The dispersion in the ZP is about 0.11 mag. This is likely a slight overestimate as in this approach the randomly drawn samples do not necessarily have the large spread in period that the true sample was selected to have.

The DM to the GC we derive based on the P2C is 14.51 ± 0.12 (random) ± 0.07 (syst). The random error could be improved further by observing additional systems when the full OGLE-III database becomes available.

Based on the serendipitously observed RR Lyrae stars in the field a DM of 14.52 ± 0.18 is derived. The error bar is for 50% due to the uncertainty in the adopted absolute magnitude of RR Lyra itself (Sollima et al.). Their PL-relation led to an LMC distance of 18.54 ± 0.15 . If instead we would *assume* the LMC distance to be 18.50 (to be consistent with the P2C calibration) then we would find a DM of 14.48 ± 0.13 (random) ± 0.07 (syst), were the systematic error comes from the uncertainty in the ZP of the observed LMC PL-relation. Like for the P2C sample, there is an additional 0.11 mag systematic uncertainty due to the limited sample size. The final DM to the GC based on the K -band RR Lyrae stars is 14.48 ± 0.17 (random) ± 0.07 (syst).

As the two distance estimates are derived independently, they can be averaged and the best empirical estimate of the DM to the GC based on the current data is 14.50 ± 0.10 (random) ± 0.07 (syst).

The theoretical WIK relation gives a formal result of 14.44 (or 14.33 with anomalous reddening) with an internal error bar of 0.04 mag. A random error of 0.11 has to be added to this, due to the limited sample, and as the theoretical relation is tied to the observed relations of M06 a similar systematic error bar of 0.07 has to be considered.

Although within the error bar of the purely empirical results, it brings up the question of reddening and the reddening law. An additional absorption in K of 0.1 mag would bring all three methods in very good agreement. On the other hand, the reddening estimates listed in Table 1 are in excellent agreement and are based on $(J - K)$ colours (Marschall et al. 2006), $(V - I)$ (Sumi 2004), and $(V - R)$ (Popowski et al. 2003). If the absorption in K were underestimated, it would also imply an underestimate of the reddening in the other maps, or a significantly higher selective reddening $A_K/A_V \sim 0.16$ instead of 0.12.

A final remark is that independent distances to some of these P2C may be obtained using surface-brightness relations (e.g. Groenewegen 2004) and the Baade-Wesselink technique. This would require better sampled K -band light curves than were needed for the present study and well-sampled radial velocity curves. Although observationally expensive it would give an improved understanding on the systematic error in the present analysis.

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References

- Busuiaux, C., & Gilmore, G. 2005 MNRAS, 358, 1309
- Bessell, M.S., & Brett, J.M. 1988, PASP 100, 1134
- Benedict, G.F., McArthur, B.E., Fredrick, L., et al. 2002, ApJ, 581, 115
- Bono, G., Caputo, F., & Santolamazza, P. 1997, A&A, 317, 171
- Bono, G., Caputo, F., Castellani, V., et al. 2003, MNRAS, 344, 1097
- Cardelli, J.A., Clayton, G.C., & Mathis, J.S. 1989, ApJ, 345, 245
- Carney, B.W., Fulbright J.P., Terndrup D.M., et al. 1995, AJ, 110, 1674
- Catchpole, R., Whitelock, P.A., Feast, M.W., et al. 1999, IAU Symposium 192, Astronomical Society of the Pacific, p. 89
- Collinge, M.J., Sumi, T., & Fabrycky, D. 2006, ApJ, 651, 197
- Di Criscienzo, M., Caputo, F., Marconi, M., & Cassisi, S. 2007, A&A 471, 893
- Eisenhauer, F., Schödel, R., Genzel, R., et al. 2003, ApJ, 597, L121
- Eisenhauer, F., Genzel, R., Alexander, T., et al. 2005, ApJ, 628, 246
- Feast, M.W., & Whitelock P.A., 1997, MNRAS, 291, 683
- Fernley, J.A., Longmore, A.J., Jameson, R.F., Watson, F.G., & Wesselink, T. 1987, MNRAS, 226, 927
- Gratton, R.G., Bragaglia, A., Carretta, E., et al. 2003, A&A, 408, 529
- Groenewegen, M.A.T. 2004, MNRAS, 353, 903
- Groenewegen, M.A.T., & Blommaert, J.A.D.L. 2005, A&A 443, 143
- Kubiak, M., & Udalski, A. 2003, AcA, 53, 117 (KU)
- Marshall, D.J., Robin, A.C., Reyle, C., Schultheis, M., & Picaud, S. 2006, A&A, 453, 635
- Matsunaga, N., Fukushi, H., & Nakada, Y., et al. 2006, MNRAS, 370, 1979 (M06)
- McNamara, D.H., Madsen, J.B., Barnes, J., & Ericksen B.F. 2000, PASP, 112, 202
- Nishiyama, S., Nagata, T., Sata, K., et al. 2006, ApJ, 647, 1093
- Paczynski, B., & Stanek, C. 1998, ApJ, 494, L129
- Popowski, P., Cook, K.H., & Becker, A.C., 2003, AJ, 126, 2910
- Pritzl, B.J., Smith, H.A., Stetson, P.B., et al. 2003, AJ 126, 1381
- Reid, M.J. 1993, ARA&A, 31, 345
- Schechter, P.L., Mateo, M.L., & Saha, A. 1993, PASP, 105, 1342
- Sollima, A., Cacciari, C., & Valenti, E. 2006, MNRAS, 372, 675
- Sumi, T., 2004, MNRAS, 349, 193
- Vanhollebeke, E., Groenewegen, M.A.T., & Girardi, L. 2008, A&A, submitted
- Walker, A.R., & Terndrup, D.M. 1991, ApJ, 378, 119
- Zucker, S., Alexander, T., Gillessen, S., Eisenhauer, F., & Genzel, R., 2006, ApJ, 639, L21